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# REPORT ON THE DEVELOPMENT OF NONDESTRUCTIVE TESTING CRITERIA FOR THE 120-MM XM830 PROJECTILE BODY

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The nondestructive testing defect criteria for the 120-mm M830 HEAT round have been developed. Based on a finite element stress analysis of launch stresses performed at ARDEC, an estimated stress intensity factor (K) solution has been determined. Fracture toughness measurements on several M830 projectile bodies are made to determine the range of fracture properties that are expected in large production of this component. The limiting sizes of allowable defects are determined by combining the K solution with the fracture toughness

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20. ABSTRACT (CONT'D)

measurements. Although no statistical analysis is performed, no launch failures of the M830 due to material defects are anticipated during its expected useful life because of the liberal safety factors used along with conservative assumptions and engineering judgment.

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## PROBLEM STATEMENT AND INTRODUCTION

The XM830 projectile body is basically a cylindrical shell fabricated from a 4140 steel forging. Its engineering purpose is to be launched from a gun tube and deliver a shaped charge penetrator to an armored target. If the projectile survives the launch, it is assumed that its intended purpose is fulfilled. This report summarizes the steps taken to establish defect criteria that insure launch survival. Fracture mechanics is used to establish the limits on allowable flaw size.

The schedule of work was as follows. Several body forgings were obtained from Honeywell, Inc. (the primary contractor). Fracture mechanics specimens were manufactured from these bodies to determine the fracture toughness of the 4140 steel. From the launch stress analysis provided by Mr. C. Larson of the Applied Sciences Division, U.S. Army ARDEC, Dover, NJ, the fracture mechanics parameter K was determined for various defect sizes at various locations in the projectile body. The allowable defect size was the largest defect which would not propagate during launch. No safety factor was applied to the resulting defect size since very conservative assumptions were used in the fracture mechanics analysis to determine K.

## EXPERIMENTAL PROCEDURES

Ten projectile bodies were received from the primary contractor. They were first subjected to a hardness test. From the results of these tests, two bodies were chosen to evaluate the fracture toughness of the 4140 steel. The two bodies chosen were that with the greatest hardness and that with the least hardness.

Fracture toughness samples were taken from two locations and in two different orientations at each location from each body chosen. The specimen layout is shown in Figure 1. The circumferential specimens give the toughness properties associated with a longitudinal defect, and the longitudinal specimens give the toughness properties associated with a circumferential defect.

The obtained specimens were loaded as shown in Figure 2. The samples were first fatigue loaded to produce a sharp crack. After precracking, the specimens were loaded to produce some additional crack growth under monotonic loading while the applied load and specimen displacement were measured. The amount of crack growth that resulted was measured by "heat tinting." The samples were placed in a furnace at an elevated temperature and the steel corroded. The corrosion product was a different color depending on how the corroding surface was formed (fatigue fracture surfaces were different from machined surfaces, etc.). This resulted in a clear marking of the amount of crack growth that occurred during the test. From the load-displacement curves, the energy dissipated by the specimen during the test was obtained by measuring the area under the curve. The area was then used to calculate the fracture mechanics parameter "the J-integral" or simply "J." The J-integral fracture toughness was determined by extrapolating a plot of J versus crack growth from several samples to the value of J that occurs with no crack growth. This toughness value can be converted to K and used to calculate maximum flaw sizes.

The authors of this report have recently established that the J-integral evaluated just after peak load in small steel samples, such as those tested here, is a good conservative measure of the toughness of the material. This is a good method of generating a large number of toughness measurements without

determining J versus crack growth curves. Using this technique, toughness values from the threaded section at two temperature extremes, -50°F and +150°F were measured. Four specimens were tested at each of these temperatures, a number which was insufficient to determine a valid J versus crack growth curve. Although this is a different approach than the standard method, it is demonstrated that this technique produces toughness measurements within about 10 percent of the toughness measured by the standard technique.

## RESULTS

The Rockwell-C hardness values of the provided projectile bodies are shown in Table I. Bodies X581, X36, and X433 were chosen for fracture toughness evaluation. The plots used to determine the J-integral toughness values are shown in Figures 3 through 9. These toughness values are also summarized in Table II, where they have been converted to the equivalent, but more convenient K values.

The toughness results show an expected trend. The lower hardness body has higher toughness than the higher hardness bodies. The circumferential properties are lower than the longitudinal toughness values. This is to be expected as the material was probably worked more during processing in the longitudinal direction.

The effect of temperature on toughness is summarized in Table III. Five specimens from the threaded section were tested at room temperature and using the extrapolation technique, a toughness of about 89 Ksi$\sqrt{in.}$ was determined. Using the J at maximum load, an average toughness of 85 Ksi$\sqrt{in.}$ was found. Thus, the J at maximum load method will probably give an estimate of toughness within less than 10 percent of the standard J test. The toughness values

reported at -50°F (65 Ksi$\sqrt{in.}$) and +150°F (76 Ksi$\sqrt{in.}$) are the average of four measurements using J at maximum load. These results show that toughness is a function of temperature. The lowest toughness measured was 65 Ksi$\sqrt{in.}$; the 4140 steel tested would probably not have a toughness value below 50 Ksi$\sqrt{in.}$ at any hardness level, orientation, or operating temperature. Therefore, in developing acceptable flaw size criteria, we decided not to allow K to exceed 25 Ksi$\sqrt{in.}$ (the expected lowest value possible divided by a safety factor of two) during launch.

## FRACTURE MECHANICS ANALYSIS

As stated, fracture mechanics was used to determine allowable flaw sizes. To accomplish this, the stress intensity factor (K) was estimated for defective bodies subjected to launch loading conditions. With the stress analysis provided by the Applied Sciences Division, all that was required was an estimate of crack sizes and geometry. We assumed that both the depth through the thickness (a) and the length along the axis (2C) could be determined. Also, we assumed that such a crack would have a semi-elliptical shape. In addition, we assumed that the stresses in the body had a uniform tensile component ($S_t$) and a pure bending component ($S_B$). This is shown schematically in Figure 10.

The stress intensity factor for a semi-elliptical crack subject to both tension and bending can be given as:

$$K = \frac{\sqrt{\pi a}\, M}{\Phi} (S_t + HS_B) \tag{1}$$

where

$$M = \{1.13 - 0.09(a/c)\} + \{-0.54 + 0.89[0.2 + (a/c)]^{-1}\}(a/B)^2 + \\ + \{0.5 - [0.65 + (a/c)]^{-1} + 14[1 - (a/c)]^{24}\}(a/B)^4$$

$$\Phi^2 = 1 + 1.464(a/c)^{1.65}$$

$$H = 1 - [1.22 + 0.12(a/c)](a/B) +$$

$$+ [0.55 - 1.05(a/c)^{0.75} + 0.47(a/c)^{1.5}](a/B)^2$$

a = crack depth through the wall thickness

2C = crack length along the surface

B = the wall thickness

Using Eq. (1) we can develop the crack size (a) and (2C) that will result in an applied K of 25 Ksi$\sqrt{in.}$ during launch.

The values of $S_t$ and $S_B$ were determined from the stress analysis provided by the Applied Sciences Division. First, the locations of the maximum occurring tensile stress ($S_{max}$) were found. The minimum stress ($S_{min}$) was that stress at the same axial location on the other side of the wall thickness. Assuming the approximation of Figure 10, $S_t$ and $S_B$ are easily found as

$$S_B = \frac{S_{max} - S_{min}}{2} \tag{2}$$

$$S_t = S_{max} - S_B \tag{3}$$

**DEFECT CRITERIA**

Using Eqs. (1), (2), and (3) the combination of a and C that results in K of 25 Ksi$\sqrt{in.}$ was determined by iteration. These results are summarized in Table IV. Some limits were set arbitrarily. First, any crack depth that is more than one-half of the wall thickness is considered too severe and should be scrapped. Second, the maximum length (2C) was restricted to 60 times the shallowest crack that produced 25 Ksi$\sqrt{in.}$ Using these allowable flaw sizes will result in no failures due to launch loading.

TABLE I. HARDNESS OF RECEIVED BODIES

| Body No. | $R_c$ Hardness |
|---|---|
| X25R | 41 |
| X36R | 39 |
| X80R | 40 |
| X391R | 42 |
| X281R | 42 |
| X421R | 40 |
| X433R | 44 |
| X441R | 42 |
| X477R | 42 |
| X581R | 44 |

## TABLE II. J-INTEGRAL TOUGHNESS

| Body | Location | Orientation | J (lbs/in.) | K (Ksi$\sqrt{in.}$) |
|---|---|---|---|---|
| X433 | Threaded | Long. | 322 | 98 |
| X581 | Threaded | Circ. | 266 | 89 |
| X581 | Thin Wall | Long. | 335 | 100 |
| X581 | Thin Wall | Circ. | 198 | 77 |
| X36 | Threaded | Circ. | 536 | 127 |
| X36 | Thin Wall | Long. | 497 | 122 |
| X36 | Thin Wall | Circ. | 272 | 88 |

TABLE III. CIRCUMFERENTIAL TOUGHNESS AT VARIOUS TEMPERATURES OF THE X581 BODY, THREADED REGION

| Temperature | Toughness (Ksi$\sqrt{in.}$) | Method |
|---|---|---|
| -50°F | 65 | Max. Load |
| Room Temp. | 89 | Extrapolation |
| Room Temp. | 85 | Max. Load |
| +150°F | 76 | Max. Load |

TABLE IV. DEFECT CRITERIA

| Location | Defect Orientation | $S_B$ (Ksi) | $S_t$ (Ksi) | a (in.) | 2C (in.) |
|---|---|---|---|---|---|
| Thin wall OD | Longitudinal | 50 | 70 | Less than 0.050 | 3.0 |
| | | | | 0.050 | 3.0 |
| | | | | 0.075 | 2.0 |
| | | | | 0.100 | 1.4 |
| | | | | 0.125 | 1.0 |
| | | | | More than 0.125 | 0 |
| Thin wall ID | Longitudinal | 30 | 50 | Less than 0.075 | 3.8 |
| | | | | 0.075 | 3.8 |
| | | | | 0.100 | 2.4 |
| | | | | 0.125 | 1.7 |
| | | | | More than 0.125 | 0 |
| Threaded ID | Circumferential | 50 | 70 | Less than 0.050 | 3.0 |
| | | | | 0.050 | 3.0 |
| | | | | 0.075 | 2.0 |
| | | | | 0.100 | 1.4 |
| | | | | 0.125 | 1.0 |
| | | | | More than 0.125 | 0 |
| Threaded OD | Circumferential | 20 | 20 | Less than 0.125 | Total Circumference |
| | | | | More than 0.125 | 0 |

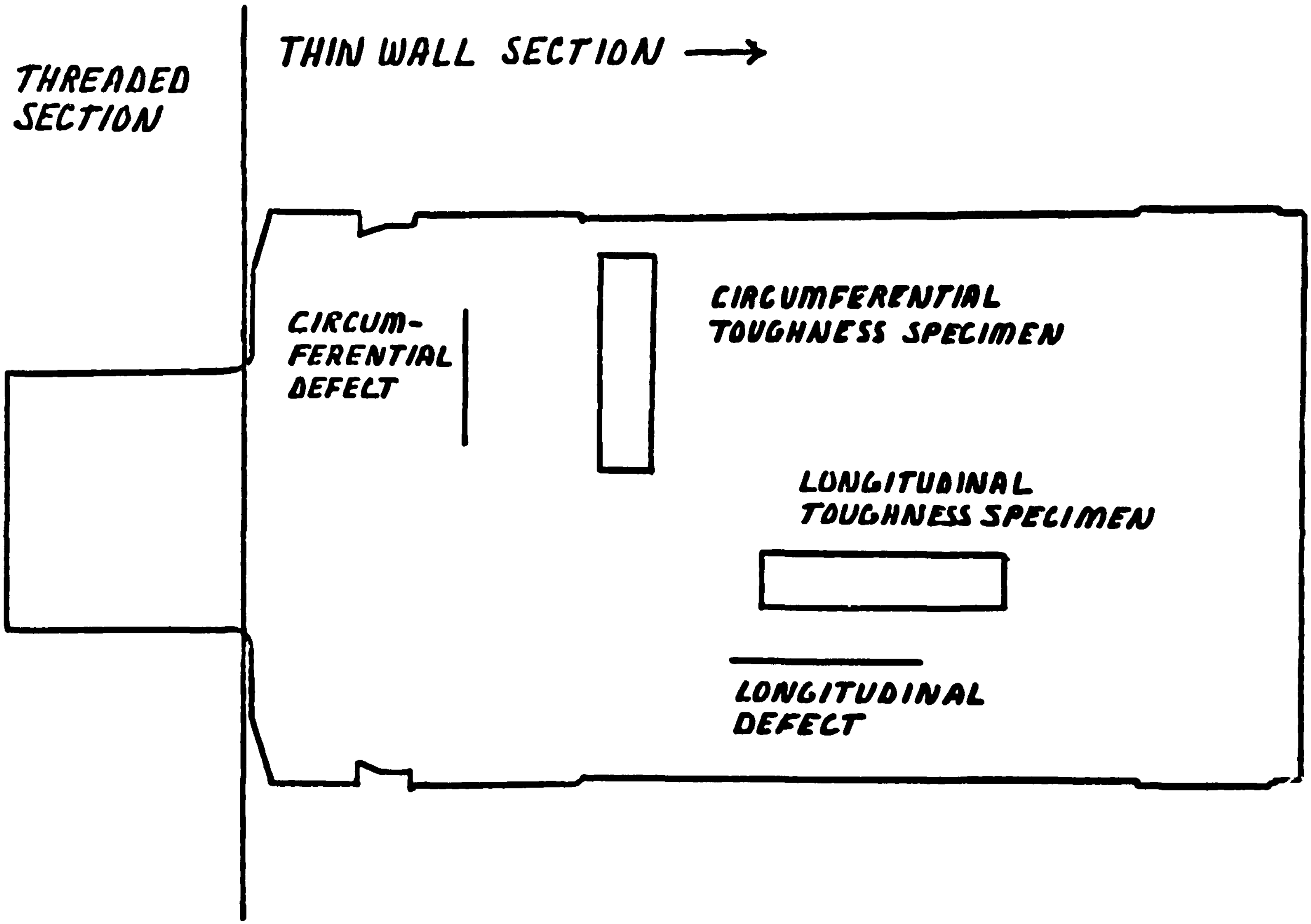


Figure 1. Layout and definitions for XM830 projectile bodies.

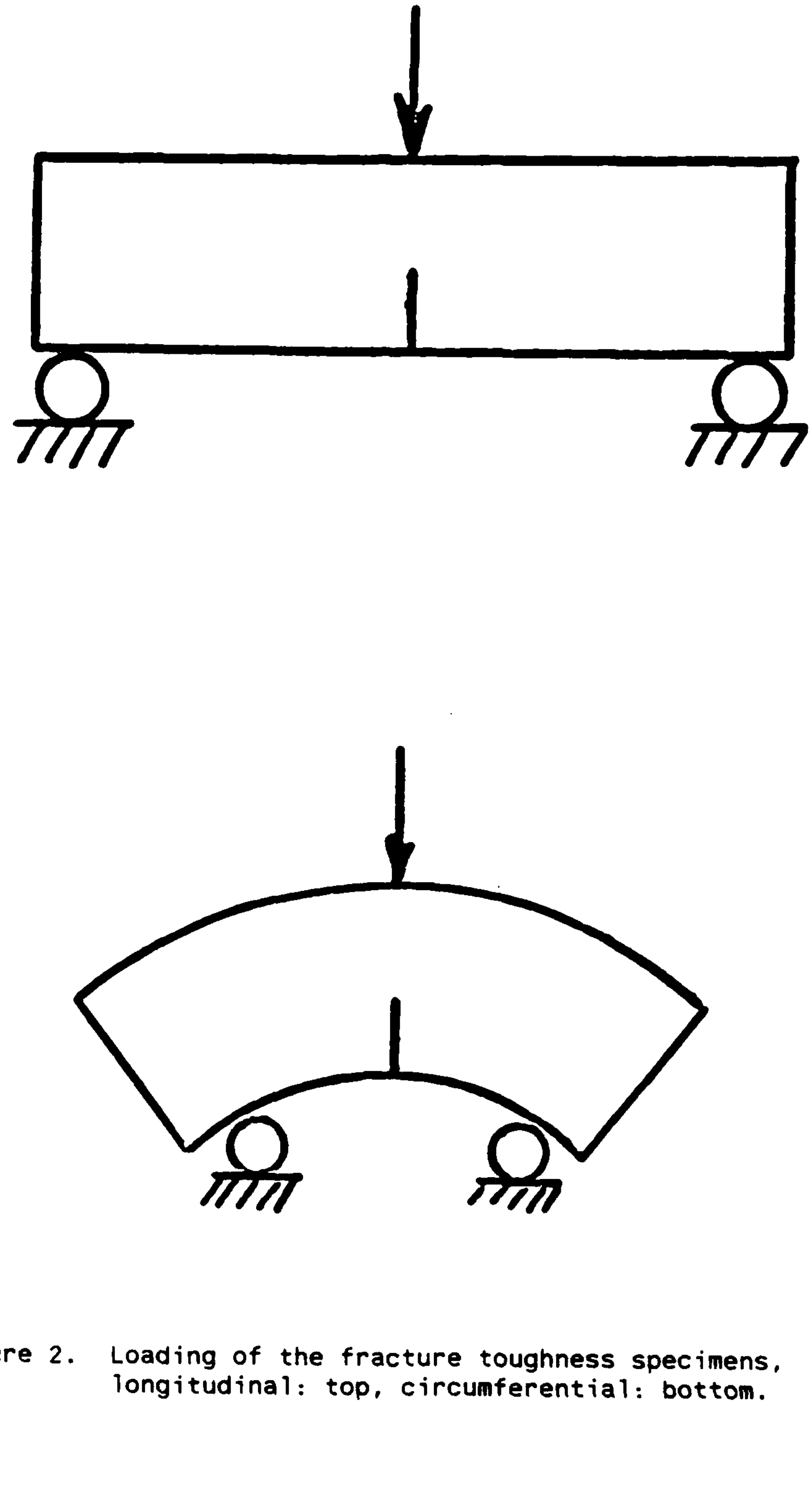

Figure 2. Loading of the fracture toughness specimens, longitudinal: top, circumferential: bottom.

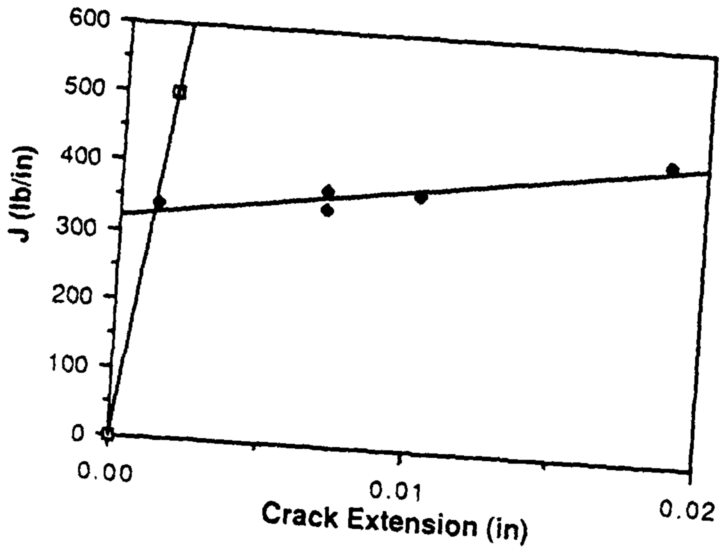


Figure 3. J-R curve for projectile body X433, threaded section, longitudinal properties.

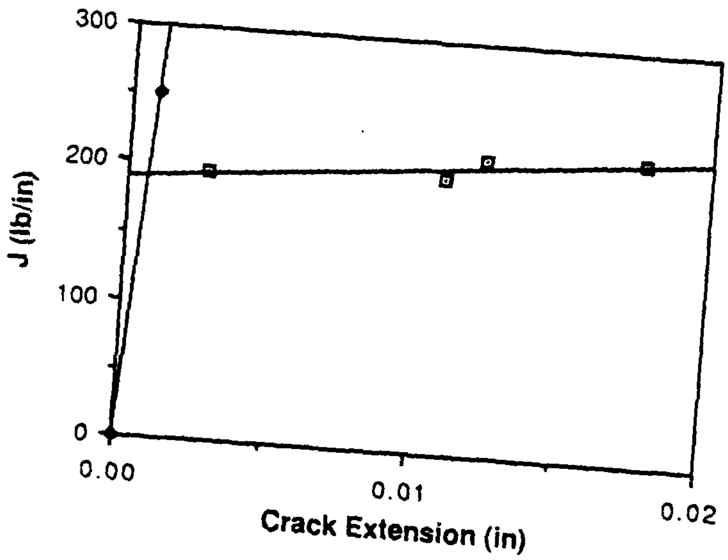


Figure 4. J-R curve for projectile body X581, threaded section, circumferential properties.

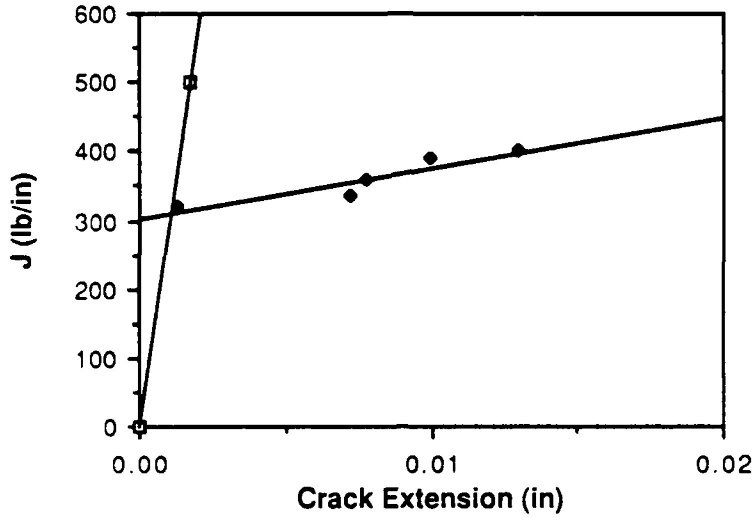


Figure 5. J-R curve for projectile body X581, thin-walled section, longitudinal properties.

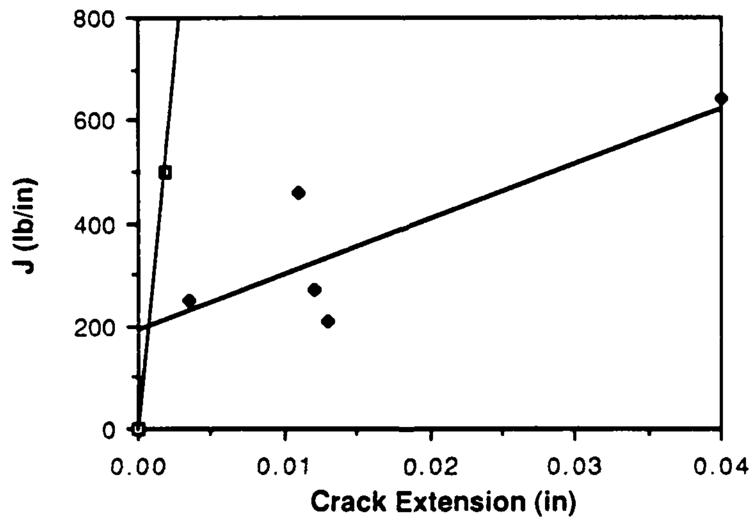


Figure 6. J-R curve for projectile body X581, thin-walled section, circumferential properties.

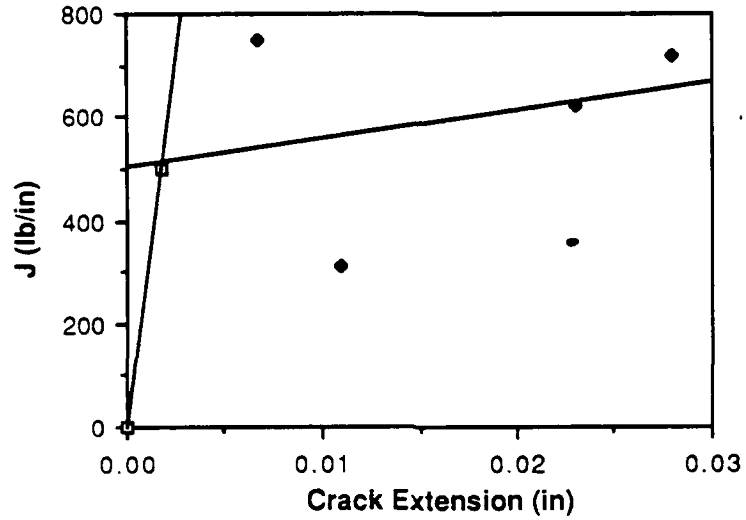


Figure 7. J-R curve for projectile body X36, threaded section, circumferential properties.

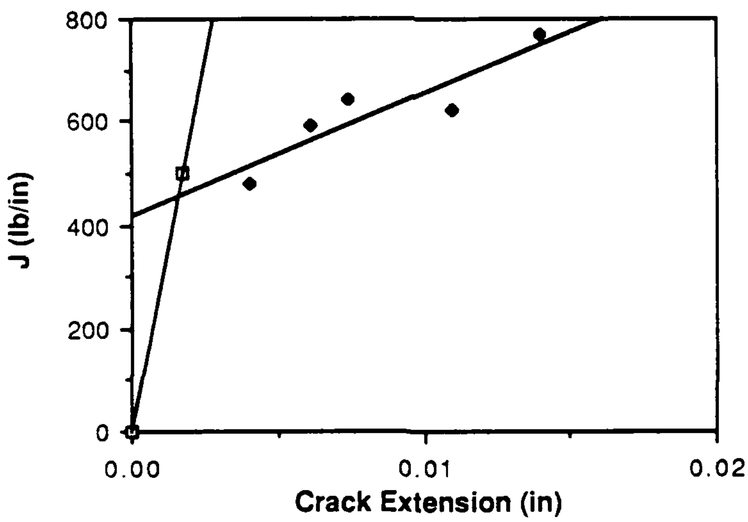


Figure 8. J-R curve for projectile body X36, thin-walled section, longitudinal properties.

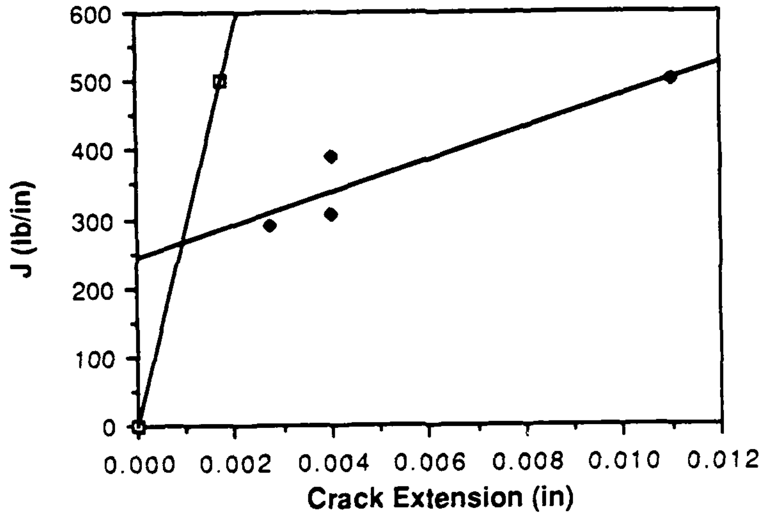


Figure 9. J-R curve for projectile body X36, thin-walled section, circumferential properties.

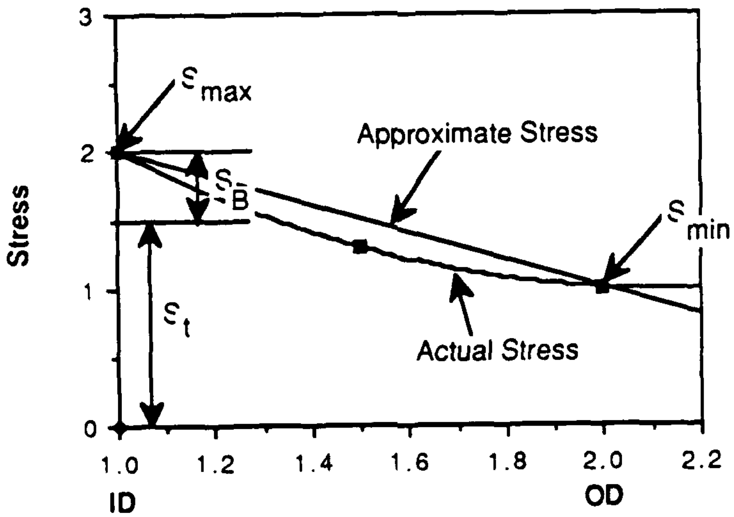


Figure 10. Linear approximation to the actual stress distribution in the projectile body during launch.

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